

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188		
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1. REPORT DATE (DD-MM-YYYY) 22-03-2011		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 1-Jul-2006 - 30-Sep-2009	
4. TITLE AND SUBTITLE Effect of Strain Rate on Fracture Initiation			5a. CONTRACT NUMBER W911NF-06-1-0232		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 611102		
6. AUTHORS Tomasz Wierzbicki			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES Massachusetts Institute of Technology Office of Sponsored Programs Bldg. E19-750 Cambridge, MA 02139 -4307			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 50465-EG.1		
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT This project focused on two key ways of improving armor design. The first method is by improvement of analysis through the development of testing techniques relevant to high-yield-strength steels under high strain rates and states of stress relevant to armor applications. This effort resulted in a novel method of testing steels under a variety of strain rates in which punch tests are performed in a drop tower. It also resulted in a proposed strain-rate dependent fracture locus.					
15. SUBJECT TERMS strain rate, fracture, armor, simulation, FEA					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Tomasz Wierzbicki
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 617-253-2104

Report Title

Effect of Strain Rate on Fracture Initiation

ABSTRACT

This project focused on two key ways of improving armor design. The first method is by improvement of analysis through the development of testing techniques relevant to high-yield-strength steels under high strain rates and states of stress relevant to armor applications. This effort resulted in a novel method of testing steels under a variety of strain rates in which punch tests are performed in a drop tower. It also resulted in a proposed strain-rate dependent fracture locus.

The second way that it contributed to improved armor design is that it investigated the efficacy of multi-steel armor as compared to traditional armor made out of only one grade of steel. It is shown that either a weight savings or gain in performance can be achieved by creating a multi-steel armor of different grades of steels through the thickness.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. Teng, X., Dey, S., Borvik, T., and Wierzbicki, T., "Protection performance of double-layered metal shields against projectile impact," Journal of Mechanics of Materials and Structures, 2007, 2(7):1307-1328.
2. Dey, S., Borvik, T., Teng, X., Wierzbicki, T., and Hopperstad, O.S., "On the ballistic resistance of double-layered steel plates: an experimental and numerical investigation," International Journal of Solids and Structures, 2007, 44: 6701-6723.
3. Mohr, D., and Gary, G., "M-shaped specimen for the high-strain rate tensile testing using a split Hopkinson pressure bar apparatus," Experimental Mechanics, 2007, 47(5): 681-692.
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Number of Papers published in peer-reviewed journals: 4.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Patents Submitted

Patents Awarded

Awards

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Carey Walters	1.00
FTE Equivalent:	1.00
Total Number:	1

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Tomasz Wierzbicki	0.00	No
FTE Equivalent:	0.00	
Total Number:	1	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Jason Chan	0.00
FTE Equivalent:	0.00
Total Number:	1

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 1.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 1.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 1.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME

Romain Bordier

Min Huang

Total Number:

2

Names of personnel receiving PhDs

NAME

Carey Walters

Total Number:

1

Names of other research staff

NAME

PERCENT SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

This research consisted of two main phases: experimental determination of the fracture of a high-strength steel under a variety of different strain rates and states of stress, and a simulation-based optimization of multi-steel armor plating with subsequent testing at NTNU in Trondheim, Norway. These two main phases of research are outlined in the following two paragraphs.

Simulation of fracture relies heavily on the history of stress and strain at the location of fracture. The sample high-strength steel was therefore first characterized for plasticity using a biaxial methodology unique to the performing organization. Following plasticity characterization, the same steel was tested for fracture initiation in quasi-static conditions. The method used for quasi-static characterization featured butterfly specimens tested in biaxial conditions, analyzed via FEA simulations of the experiments. The effect of high strain rates was determined by a series of punching experiments which were carried out in a drop tower at speeds up to 15 m/s. By changing the geometry of the punch specimens, the state of stress was varied over a range relevant to military applications. Changing drop mass and velocity allowed the experimenter to control the strain rate history of the material. Finally, quasi-static punch tests were compared to the butterfly experiments to confirm that they produce similar answers and can be compared directly. From this research, a new, strain-rate dependent fracture locus is proposed.

The other phase of this project featured a number of simulations to find an optimal combination of multiple grades of steel to create a multi-steel armor plate. Within these simulations, a generic projectile representative of military projectiles was simulated impacting onto monolithic high strength plates, plates with gaps, and plates consisting of both high-strength and low-strength steels. It was found that some of the options were more weight-economical than monolithic high strength plates. This was because gaps between plates or steels with multiple grades were seen to create a blunting effect, thus redistributing the impulse associated with the projectile over a wide area of the secondary armor plating. Test at the structural level are currently conducted at NTNU.

Technology Transfer

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6. AUTHOR(S) Wierzbicki, Tomasz				5d. PROJECT NUMBER								
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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)					10. SPONSOR/MONITOR'S ACRONYM(S)							
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15. SUBJECT TERMS Fracture initiation, strain rate, triaxiality												
16. SECURITY CLASSIFICATION OF: <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 33%; padding: 2px;">a. REPORT</td> <td style="width: 33%; padding: 2px;">b. ABSTRACT</td> <td style="width: 33%; padding: 2px;">c. THIS PAGE</td> </tr> <tr> <td style="text-align: center; padding: 2px;">U</td> <td style="text-align: center; padding: 2px;">U</td> <td style="text-align: center; padding: 2px;">U</td> </tr> </table>			a. REPORT	b. ABSTRACT	c. THIS PAGE	U	U	U	17. LIMITATION OF ABSTRACT UU		18. NUMBER OF PAGES	
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					19b. TELEPHONE NUMBER (Include area code) 617-253-2104							

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**Project Summary - Grant # 50465-EG
(Reporting Period: October 2006 – September 2009)**

Effect of Strain Rate on Fracture Initiation

Tomasz Wierzbicki
Dept of Mechanical Engineering
Massachusetts Institute of Technology, Cambridge, MA 02139- 4307

Abstract

This project focused on two key ways of improving armor design. The first method is by improvement of analysis through the development of testing techniques relevant to high-yield-strength steels under high strain rates and states of stress relevant to armor applications. This effort resulted in a novel method of testing steels under a variety of strain rates in which punch tests are performed in a drop tower. It also resulted in a proposed strain-rate dependent fracture locus.

The second way that it contributed to improved armor design is that it investigated the efficacy of multi-steel armor as compared to traditional armor made out of only one grade of steel. It is shown that either a weight savings or gain in performance can be achieved by creating a multi-steel armor of different grades of steels through the thickness.

Objective

The objective of the research conducted in this grant was to develop experimental and numerical procedures to characterize dynamic plastic and fracture properties for a class of armor steels of interest to the Army and predict high-velocity impact events. This is accomplished through the use of a novel experimental technique that is being developed at MIT in conjunction with Ecole Polytechnique in France and NTNU in Norway. The modified fracture locus, which depends on the stress triaxiality, the Lode angle parameter, and the equivalent plastic strain rate, is described in this report. Simulations have been used maximize the ballistic limit by changing the material and structural configuration of armor plates.

Approach

This research consisted of two main phases: experimental determination of the fracture of a high-strength steel under a variety of different strain rates and states of stress, and a simulation-based optimization of multi-steel armor plating with subsequent testing at NTNU in Trondheim, Norway. These two main phases of research are outlined in the following two paragraphs.

Simulation of fracture relies heavily on the history of stress and strain at the location of fracture. The sample high-strength steel was therefore first characterized for plasticity using a biaxial methodology unique to the performing organization. Following plasticity characterization, the same steel was tested for fracture initiation in quasi-static conditions. The method used for quasi-static characterization featured butterfly specimens tested in biaxial conditions, analyzed via FEA simulations of the experiments. The effect of high strain rates was determined by a series of punching experiments which were carried out in a drop tower at speeds up to 15 m/s. By changing the geometry of the punch specimens, the state of stress was varied over a range relevant to military applications. Changing drop mass and velocity allowed the experimenter to control the strain rate history of the material. Finally, quasi-static punch tests were compared to the butterfly experiments to confirm that they produce similar answers and can be compared directly. From this research, a new, strain-rate dependent fracture locus is proposed.

The other phase of this project featured a number of simulations to find an optimal combination of multiple grades of steel to create a multi-steel armor plate. Within these simulations, a generic projectile representative of military projectiles was simulated impacting onto monolithic high strength plates, plates with gaps, and plates consisting of both high-strength and low-strength steels. It was found that some of the options were more weight-economical than monolithic high strength plates. This was because gaps between plates or steels with multiple grades were seen to create a blunting effect, thus redistributing the impulse associated with the projectile over a wide area of the secondary armor plating. Test at the structural level are currently conducted at NTNU.

Relevance to Army

The fracture methodology under investigation can be used for a full range of ductile metals, to include materials used in both armor and projectiles. This program will also produce a calibrated fracture locus for at least one material that is relevant to Army applications. With the methodology and a calibrated fracture locus, the Army and its contractors will be able to better simulate a variety of phenomena that feature fracture at high strain rates. The penetration of thick armor by a kinetic energy weapon is an excellent example of an application of this methodology because it features fracture under a wide variety of stress triaxialities at a high strain rates for both the armor and the projectile. Another example would be to have a better insight into the problem of preventing spallation of High Hard armor shields, recently reported by the DoD.

Accomplishments for the funding Period

1. A novel plasticity method was developed that featured biaxial testing of a specimen that is not thinned in the gage area. This was compared to an already-published biaxial plasticity testing technique in which the thickness is reduced.
2. A comparison was made between test data found from biaxial butterfly specimens and punch-style testing. This is the first time that such a comparison has been made.
3. A new experimental methodology featuring dynamic punch testing has been developed and demonstrated.
4. A modification to the previously-published Modified Mohr-Coulomb fracture criteria has been suggested to allow for strain rate sensitivity in both the plasticity and fracture locus.
5. A unique M-shaped specimen has been developed for use in dynamic testing (both the drop tower and the Hopkinson bar) that features plane strain tension conditions and very low inertia due to gripping.
6. A new device has been designed, manufactured, and demonstrated that can be used for testing shear plasticity at high strain rates, both in the drop tower and the Hopkinson bar.
7. A new device has been designed and manufactured that can be used for testing tensile plasticity at high strain rates in the drop tower. This device features very low inertia due to gripping, which is critical for good dynamic testing.
8. The material parameters for a sample high strength material have been calculated for:
 - a. Anisotropic plasticity
 - b. Static fracture
 - c. Dynamic fracture
9. Simulations have been carried out assessing the affect of a gap between armor steel plates.
10. Simulations have been carried out assessing the affect of having multiple grades of steel in the same armor plate.
11. The ballistic perforation resistance of double-layered steel plates impacted by blunt and ogival projectiles was further investigated experimentally, and the results were presented at the recent International Conference on Computational Structures Technology in Athens, Greece.
12. Dynamic compression and punch indentation tests on polycarbonate sheets and cylinders were carried out in support of a separate project. During that testing program, a combination of polycarbonate and PMMA was tested under dynamic conditions.

Collaborations and Technology Transfer

- Even before the present project was chosen for funding, ICL developed close working relations with Dr. Todd Bjerke, Dr. Bryan Cheeseman, and Dr. Tusit Weerasooriya of the ARL's Weapons and Materials Research Directorate.

- A close working relationship was developed in the last year with a group of researchers at the Structural Impact Laboratory at the Norwegian University of Science and Technology, led by Professor Tore Borvik. Currently, all the tests in our joint MIT/NTNU project are run in Trondheim.
- Professor Dirk Mohr, who is co-directing the Dynamic Testing Lab at the Department of Solid Mechanics of Ecole Polytechnique, spent part of his sabbatical leave at MIT. He brought to ICL considerable experience in dynamic material testing and made his lab facilities accessible to MIT students. In fact, JongMin Shim, who was a Ph.D. candidate at the ICL during this project, visited his lab in France twice and conducted experiments on the Hopkinson Pressure bars there.
- The results of the present project will be of great use for two related projects conducted at ICL and supported by the Office of Naval Research.
- Dr. JongMin Shim and Dr. Carey Walters both worked on this project during their times at MIT, and both of them have moved into positions in which they apply the techniques and skills developed in this project. Carey Walters is a researcher on high-strength steel structures at TNO, and JongMin Shim is a post-doc at Harvard.

Resulting Journal Publications

1. Teng, X., Dey, S., Borvik, T., and Wierzbicki, T., "Protection performance of double-layered metal shields against projectile impact," *Journal of Mechanics of Materials and Structures*, 2007, **2**(7):1307-1328.
2. Dey, S., Borvik, T., Teng, X., Wierzbicki, T., and Hopperstad, O.S., "On the ballistic resistance of double-layered steel plates: an experimental and numerical investigation," *International Journal of Solids and Structures*, 2007, **44**: 6701-6723.
3. Mohr, D., and Gary, G., "M-shaped specimen for the high-strain rate tensile testing using a split Hopkinson pressure bar apparatus," *Experimental Mechanics*, 2007, **47**(5): 681-692.
4. Borvik, T., Dey, S., Hopperstad, O. S., Wierzbicki, T. and Teng, X., "Ballistic Resistance of Double-Layered Metal Plates," *Proceedings of the Ninth International Conference on Computational Structures Technology*, Athens, Greece, September 2008.

Graduate Students Involved During the Project Period

- Dirk Mohr (Visiting Professor from Ecole Polytechnique, Palaiseau, France)
- Carey Walters (Ph. D. recipient)
- Min Huang (M.S. student)

- Romain Bordier (M.S. student)
- Jason Chan (B.S. student)

Awards, Honors and Appointments

- None relevant to the present program.



Tomasz Wierzbicki
Massachusetts Institute of Technology
Cambridge, MA





Objectives



The objective of the proposed research is to develop experimental and numerical procedures to characterize the effect of strain rate sensitivity on fracture properties for a class of high strength steels and/or armor steels of interest to the Army in order to predict high-velocity impact and explosion events.



Motivation



1. The capabilities of the Rolled Homogenous Armor (RHA) steel , of which most metallic armors are made, have now been fully exhausted.
2. Recent documents revealed by the DoD demonstrated that armor for light tactical vehicles made from High Hard Steel may develop many fragments due to spallation, which could enter the passenger compartment.
3. The major scientific challenge is to develop new fracture model with strain rate sensitivity for implementation in commercial FE codes.



Approach



The approach to this project was two-phased: fracture characterization at high strain rates, and development of a multi-steel armor.

Phase 1: Quasi-static and dynamic tests were performed to determine the plasticity and fracture properties of a high-strength steel. Quasi-static biaxial plasticity and fracture experiments were carried out. Dynamic fracture properties were determined from punch tests performed in an instrumented drop tower.

Phase 2: Parallel to the material characterization, a simulation-based study was performed to optimize a steel made out multiple layers of dissimilar steel.



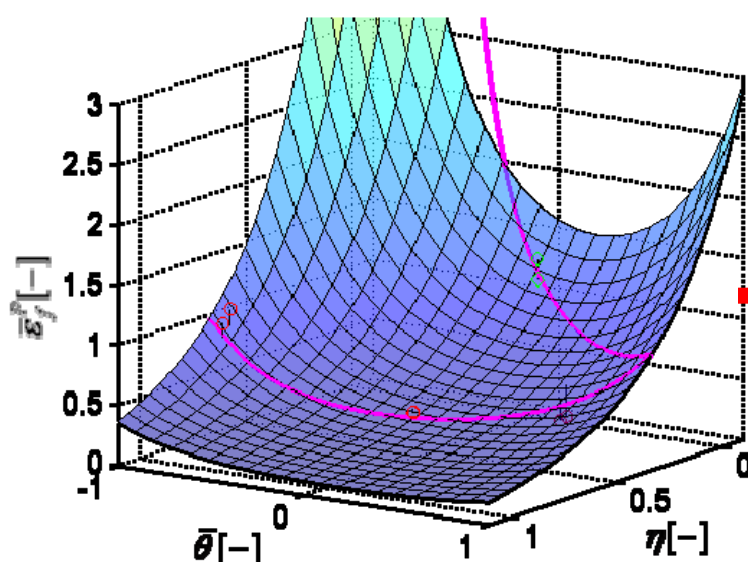
Phase 1: High strain rate fracture of high strength steel



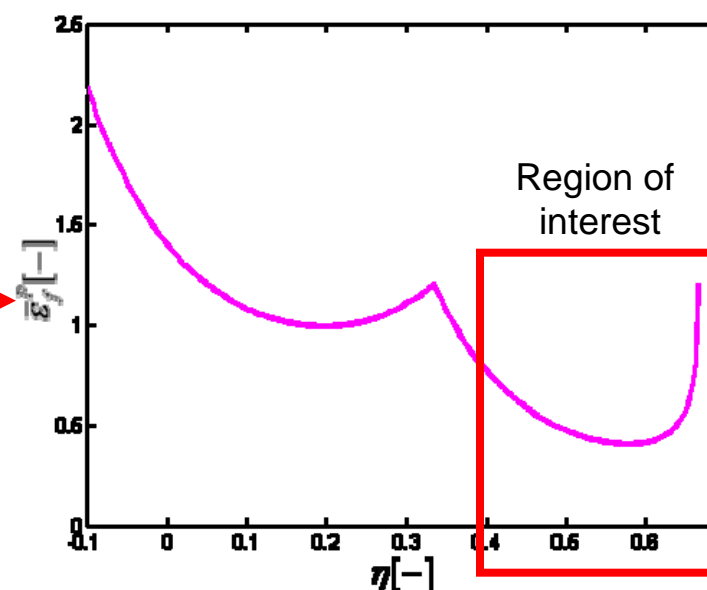
Background: 3-D Fracture Locus



The starting point of this research is the previously-developed Modified Mohr-Coulomb fracture criterion. This was calibrated for the steel being studied and shown graphically below as the relationship between ductility (vertical axis), triaxiality (η), and Lode angle ($\bar{\theta}$).



Plane stress assumption

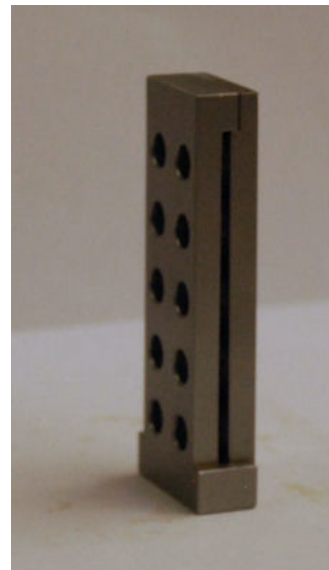
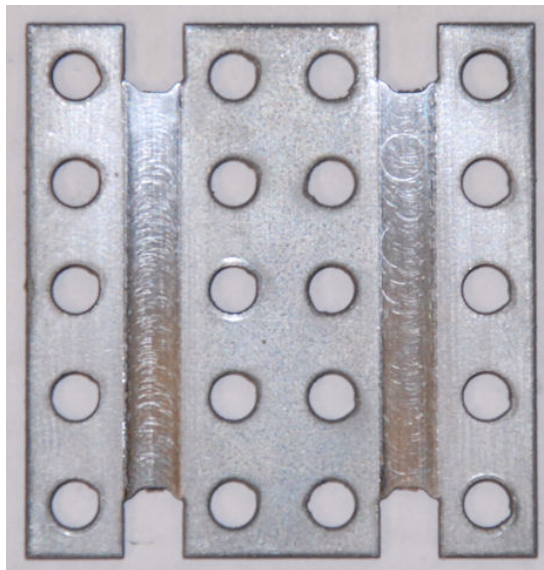


New Shear Testing Apparatus for Drop Tower

by Romain Bordier, Masters student



A new apparatus for testing plasticity in shear at high strain rates was designed, built, and demonstrated in this project. The specimen is shown below (left), followed by the center, stabilizing section (center), and finally the full assembly (right).

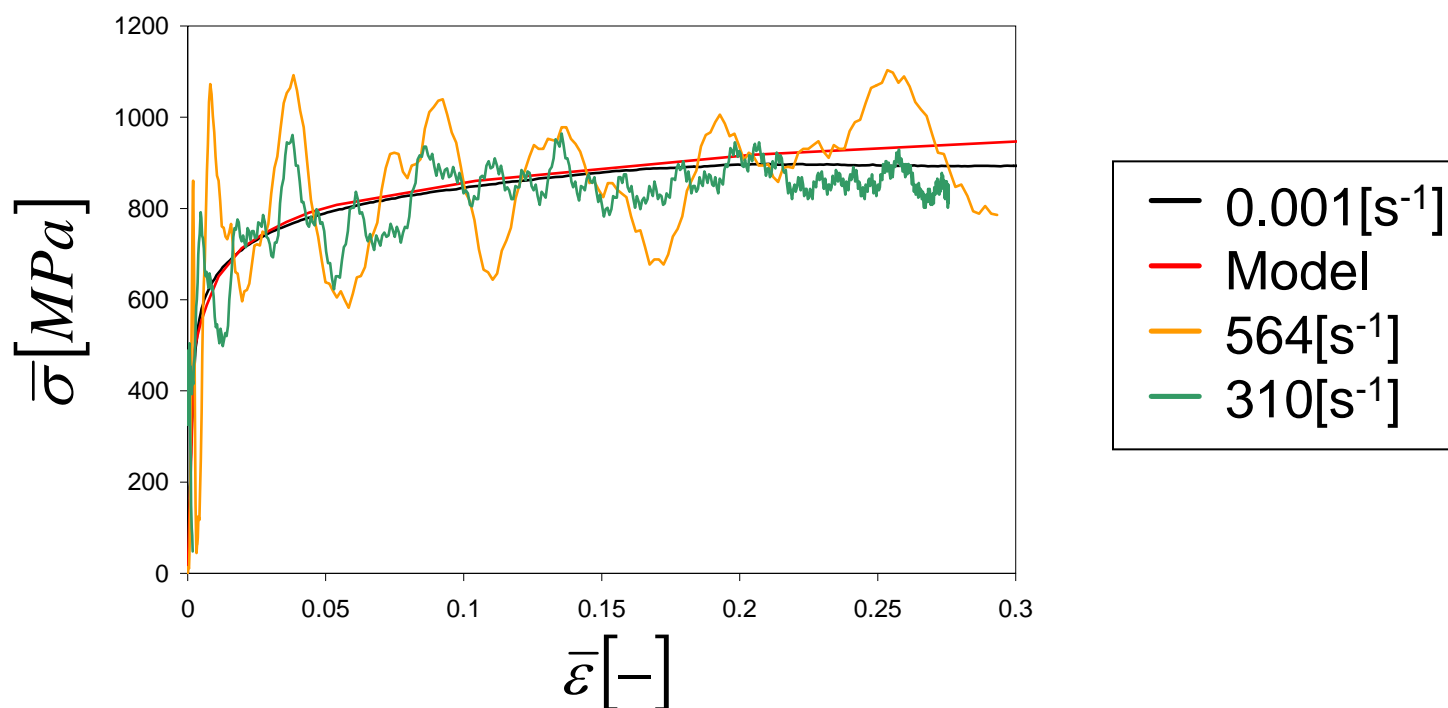




Stress-Strain curves measured in shear at different strain rates



With the apparatus described in the prior slide, the effect of strain rate on plasticity was measured. The noise is due to the instantaneous acceleration of the stabilizing section rather than a material property. It is unfortunately unavoidable, but is comparable or better here than in other published works.



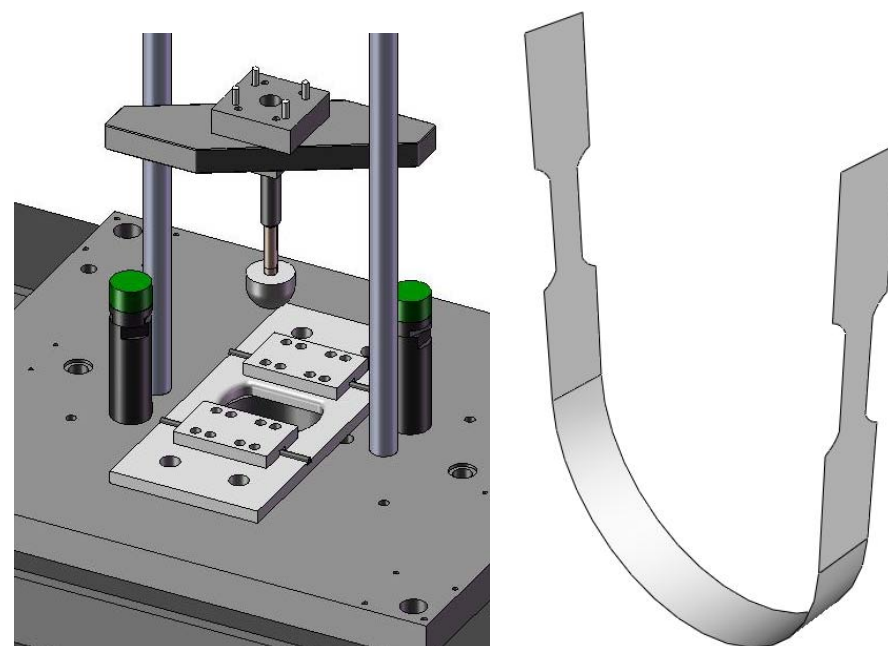
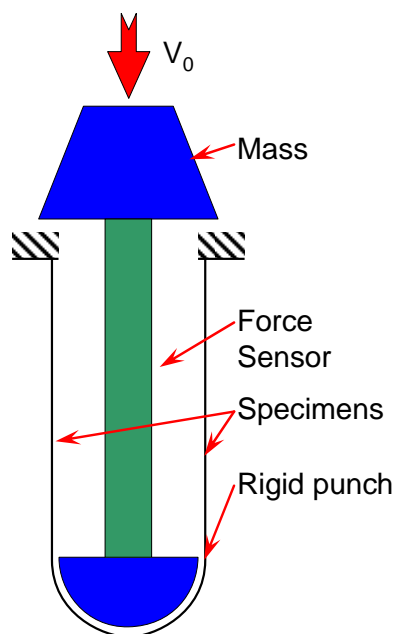


Dynamic tensile experiment

by Jason Chan, undergraduate



A second way of finding dynamic plasticity parameters was developed as an undergraduate thesis during this project. With this method, symmetrical tension specimens are tested by a drop tower punch. This method has the advantage that there is negligible mass associated with gripping that needs to be accelerated during the test.

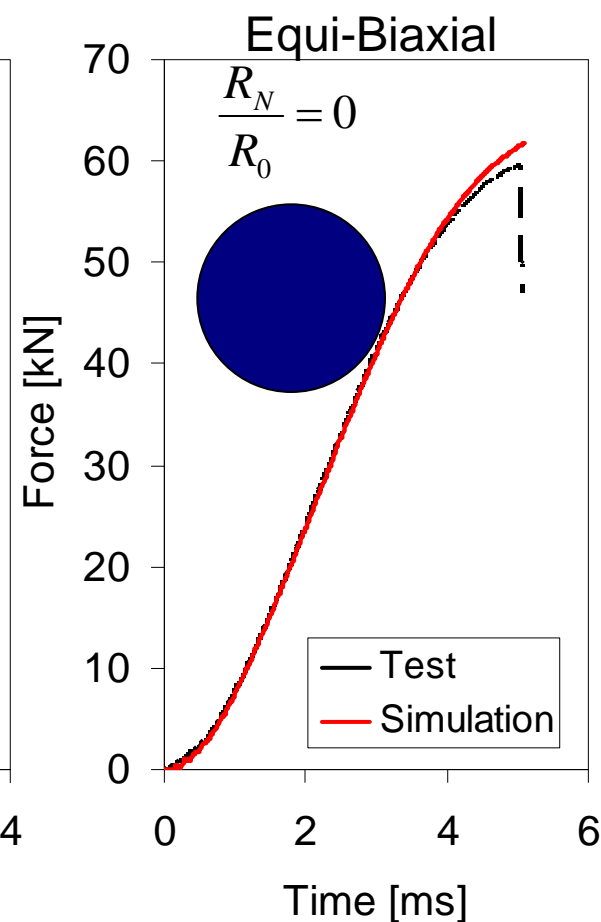
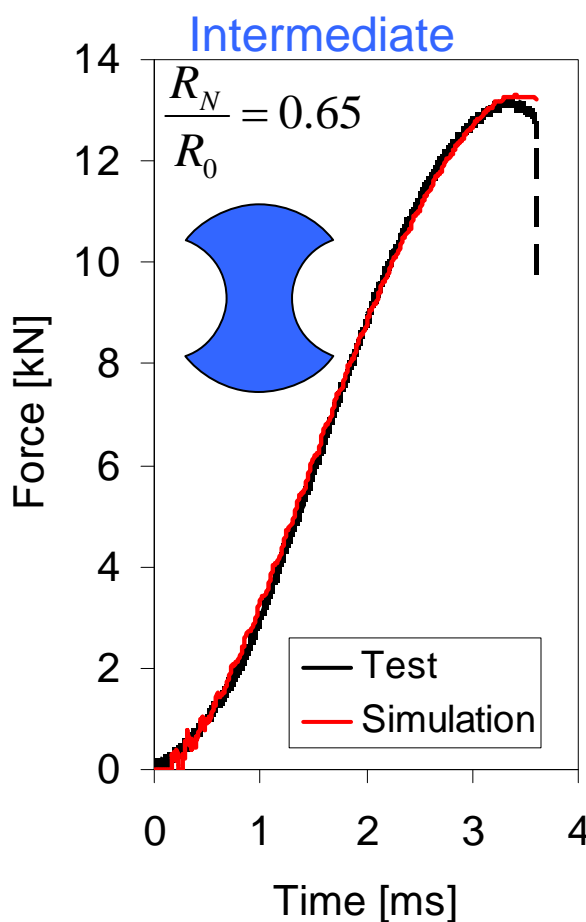
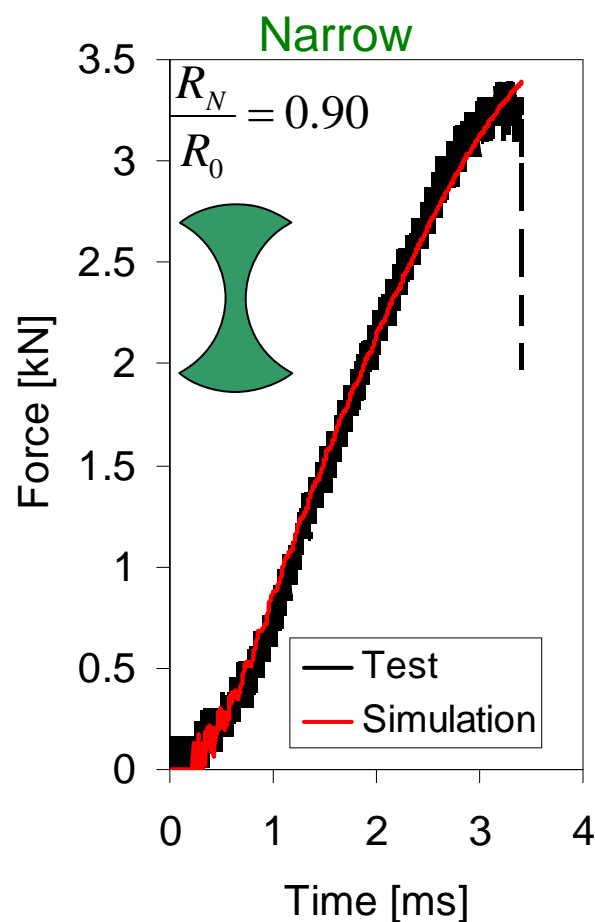




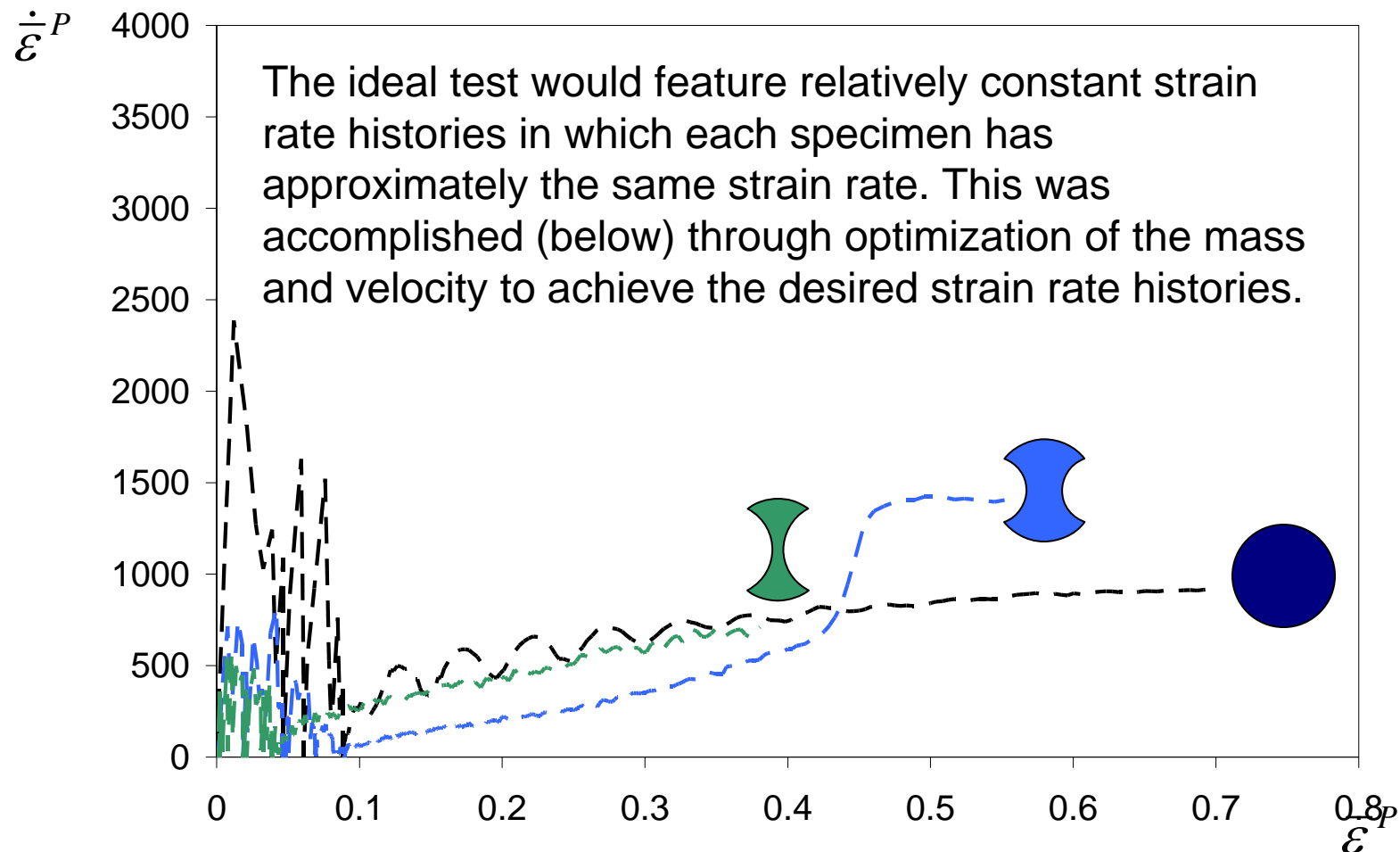
Comparison of Test Results with Simulation (ABAQUS Shell model)



The favorable comparison (below) allows simulation to be used for interpretation of of the tests.



Selection of Dynamic Conditions: High Velocity Case

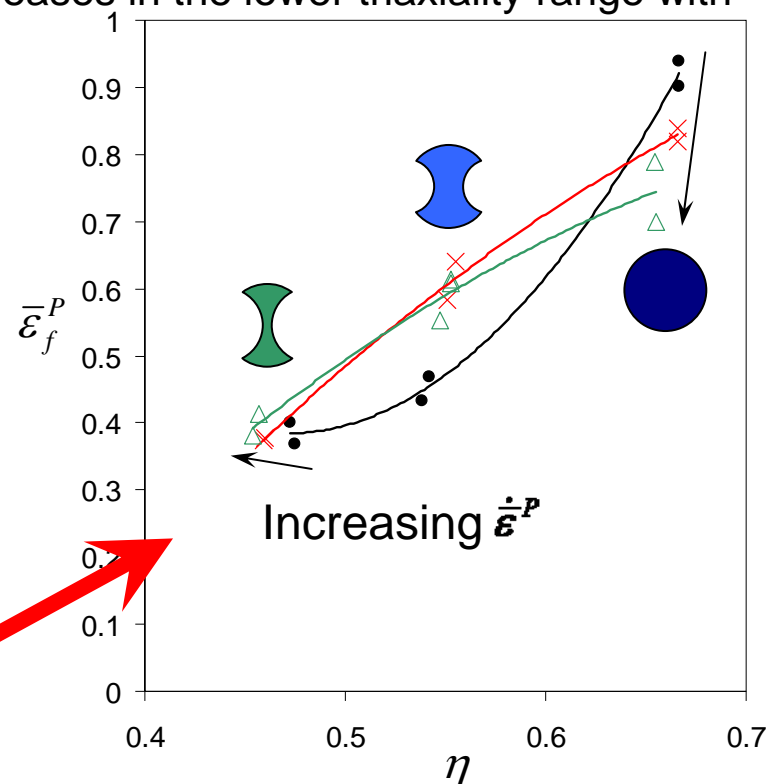
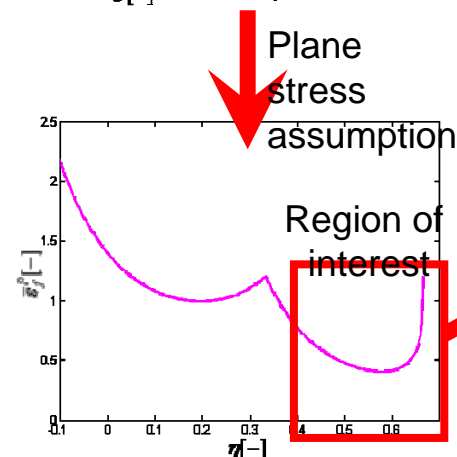
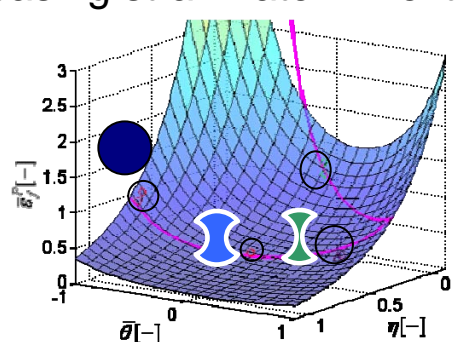




Results in context of fracture locus



The quasi-static fracture locus is shown on the top left. The projection onto the ductility versus stress triaxiality plane is shown bottom, and a focused area on that projection is shown on the right. This shows that over the region of interest, ductility decreases in the high triaxiality range with increasing strain rate while it increases in the lower triaxiality range with increasing strain rate.





Modification of fracture locus



Based on the outcome of the research, a change to the quasi-static fracture locus is suggested. The quasi-static fracture locus (developed previously) is:

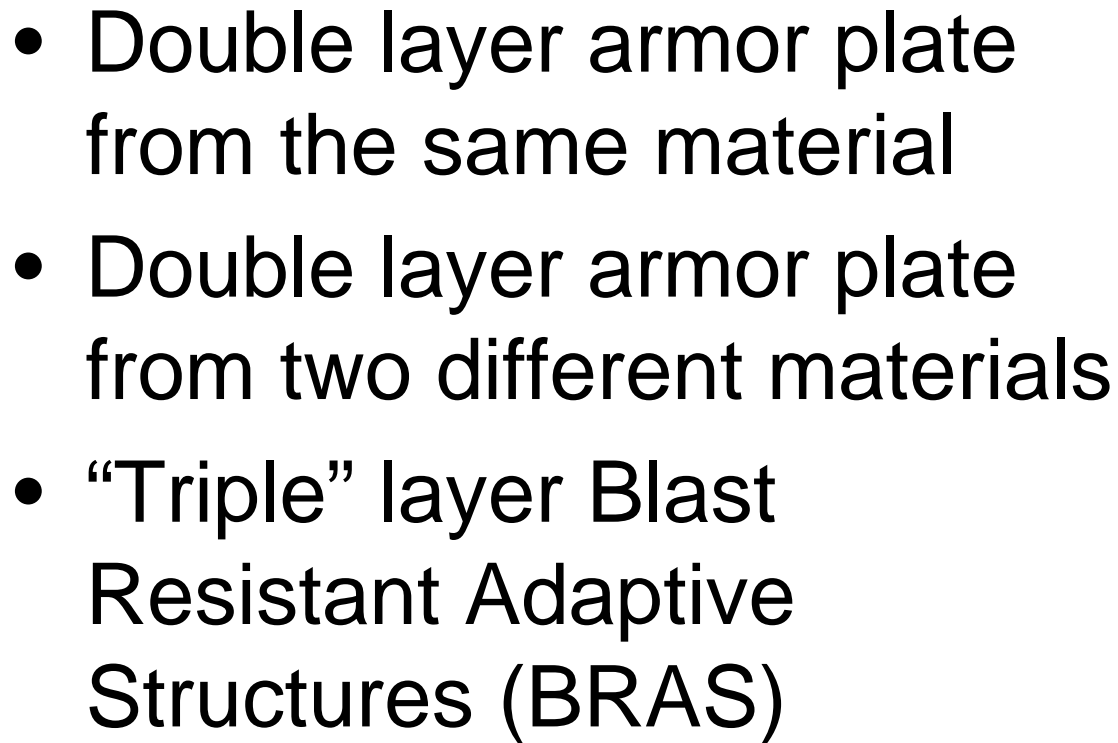
$$\bar{\varepsilon}_f = \left\{ \frac{A}{c_2} \left[c_3 + \frac{\sqrt{3}}{2 - \sqrt{3}} (1 - c_3) \left(\sec\left(\frac{\bar{\theta}\pi}{6}\right) - 1 \right) \right] \left[\sqrt{\frac{1 + c_1^2}{3}} \cos\left(\frac{\bar{\theta}\pi}{6}\right) + c_1 \left(\eta + \frac{1}{3} \sin\left(\frac{\bar{\theta}\pi}{6}\right) \right) \right] \right\}^{-\frac{1}{n}}$$

Based on this research, the Cowper-Symonds plasticity law has been incorporated, one of the fracture constants has been eliminated, and the remaining two are made to be dependent on strain rate:

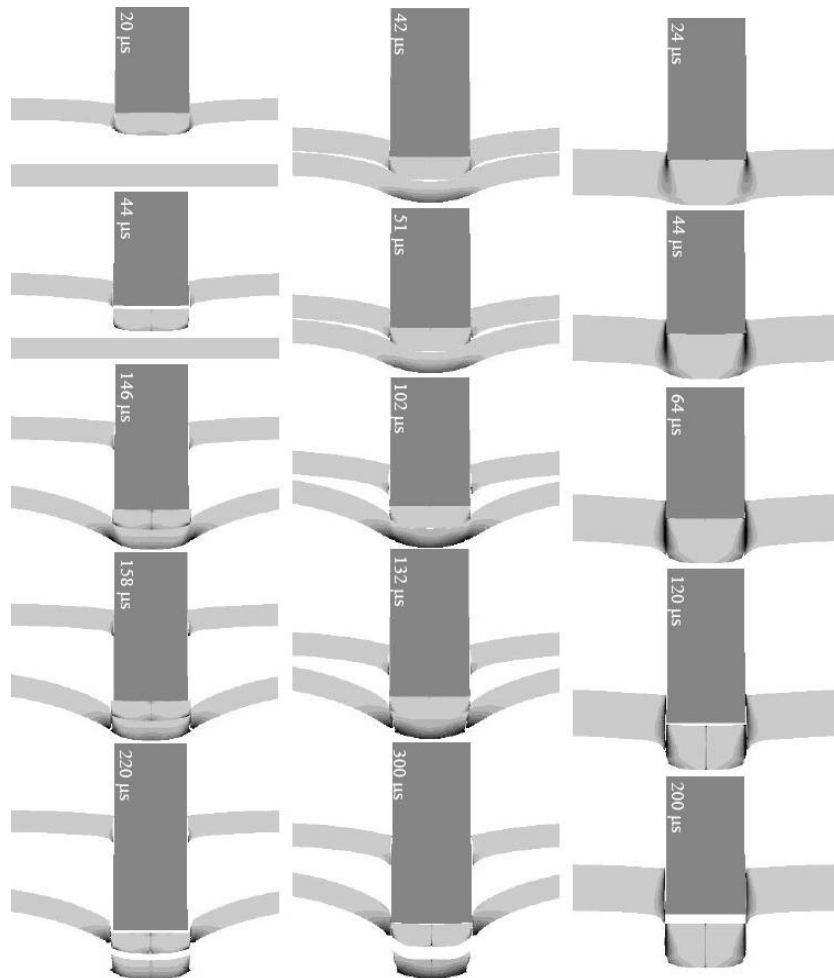
$$\bar{\varepsilon}_f^p = \left\{ \frac{C}{c_2(\dot{\varepsilon})} \left[1 + \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^{1/n_{cs}} \right] \left[\left(\sec\left(\frac{\bar{\theta}\pi}{6}\right) - 1 \right) \left[\sqrt{\frac{1 + c_1(\dot{\varepsilon})^2}{3}} \cos\left(\frac{\bar{\theta}\pi}{6}\right) + c_1(\dot{\varepsilon}) \left(\eta + \frac{1}{3} \sin\left(\frac{\bar{\theta}\pi}{6}\right) \right) \right] \right] \right\}^{-\frac{1}{n_H}}$$



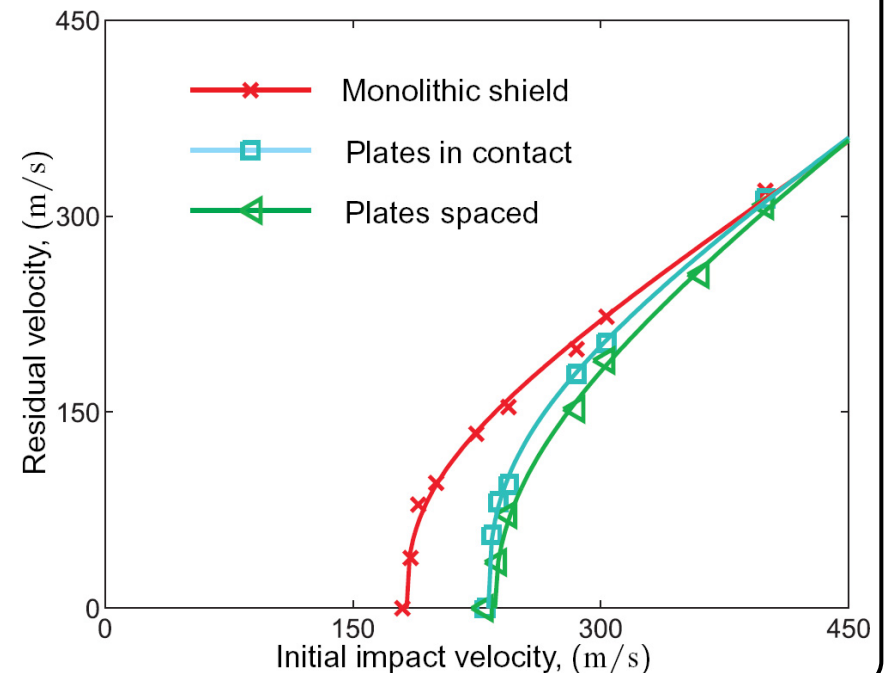
Part 2: Multi-steel armor plating



Advantages of a Double Layer Armor over Monolithic Armor



LS-DYNA Simulation of the perforation process of three types of target plates struck by a flat-nosed projectile. The plot below shows the benefits of a double-layer plate configuration.



Example of Technology Transfer to Army and DoD



Thickness

6 mm

(6)-blunt-05

12 mm

(12)-blunt-07

2x6 mm

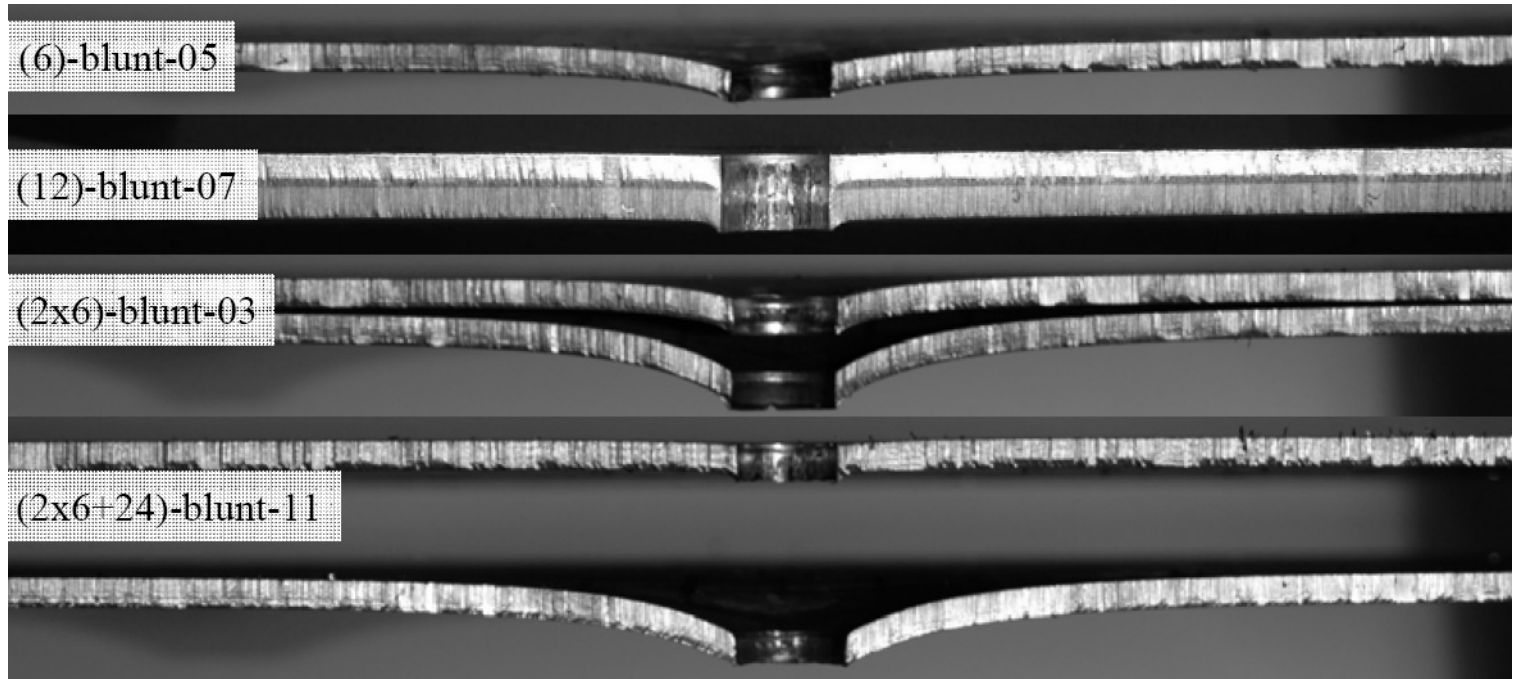
In contact

(2x6)-blunt-03

2x6 mm

24 mm gap

(2x6+24)-blunt-11

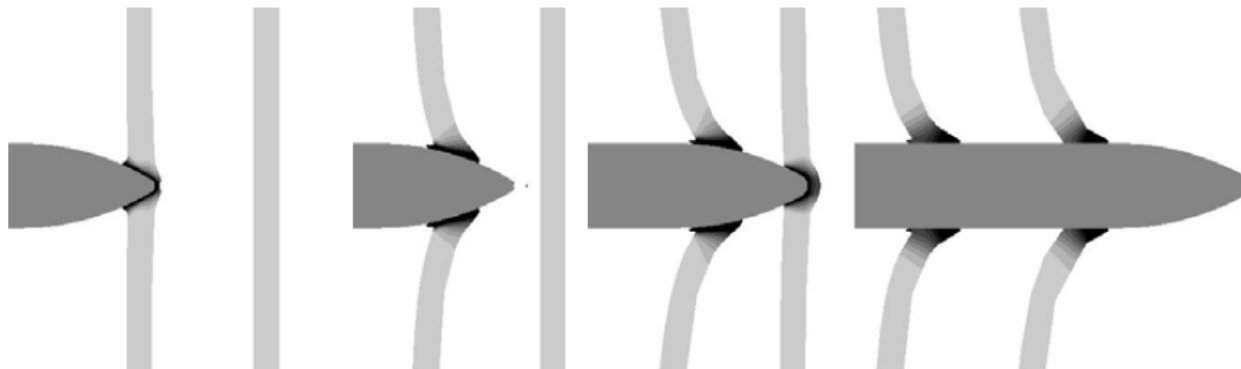
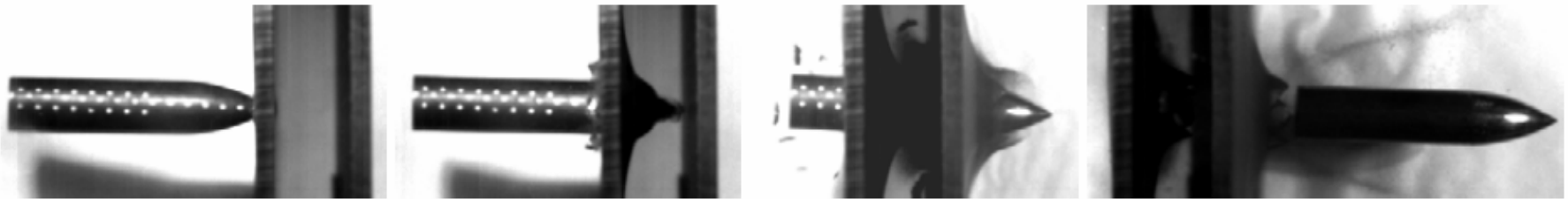


Final shapes of perforated plates at impact velocities close to respective ballistic limits.

Example of Technology Transfer to Army and DoD-con't

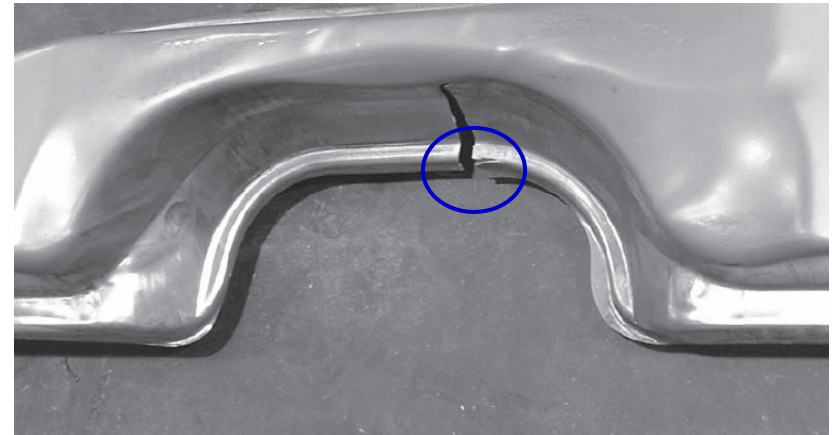
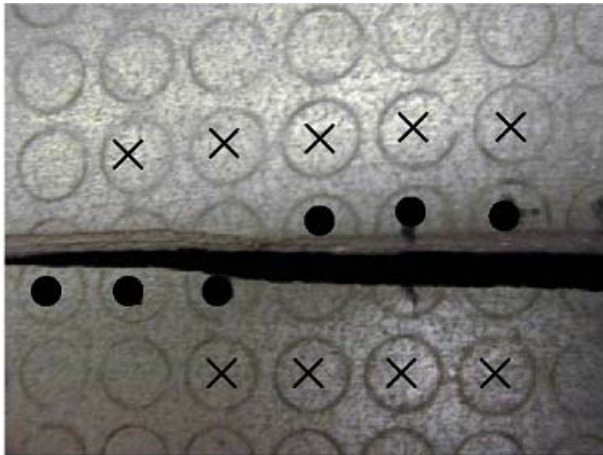


Initial velocity of the ogival projectile 289.5 m/s



LS-DYNA simulation with the fracture option

Examples of Technology Trasfer to Industry



The MIT-Industry consortium on Advanced High Strength Steels is developing practical tools and providing material data for predicting fracture in the Industrial Environment.



Transitions

(DoD and industry research teams interested in our work)



DoD Teams:

Dr. Todd Bjerke, Dr. Bryan Cheeseman, and Tusit Weerasooriya of the ARL Weapons and Materials Research Directorate

Dr. Thomas Moyer, head of Survivability at the Naval Surface Warfare Center

Industrial Teams:

Dr. Ming F. SHI, US Steel

Dr. Thomas B. STOUGHTON, GM

Dr. Nripen SAHA, Ford Motor Company

Dr. Benda YAN, Arcelor/Mittal

Dr. Hong ZHU, Arcelor/Mittal



PI Awards



- A special grant of \$100K in 2005/2006 awarded to the Impact and Crashworthiness Lab by ARL's Weapons and Materials Research Directorate